Design Proposal: Binary photonic switch based on the Mach-Zehnder interferometer with a half-ring resonator as ΔL

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Abstract:

This report describes the design of a Mach-Zehnder interferometer, combined with an optical half-ring resonator in the ΔL segment. The aim of adding a ring resonator to the MZI device is to observe the passive optical switching capabilities and FSR deviation upon different input configurations. **The expectations are to achieve all-optical switching nanophotonic device, in which a control beam releases and blocks the flow of the main one.**

1. Introduction

For more than 20 years we have been expriencing the evolution of the conventional electronic computing - including storage, central processing units and coprocessors. All of the electronic industry relies on semiconductor logic and memory, based on transistors. Nowadays the technology is on the verge of the Moore's Law limits. Keeping the pace for performance increase comes at the cost of new manufacturing powers for smaller transistors. A lot of older fabrication plants get either abandoned or transmormed for manufacturing of less demanding semiconductor components - like microcontrollers, chipsets and transceivers.

Silicon photonics is one of the most promising candidates for the future of computing. Light is harder to control than electric current within P-N junctions and that leads to signifacantly larger structures within a photonic integrated circuit. But this also has a positive side - this cutting-edge technology could utilise the older CPU manufacturing nodes for research and development of innovative all-optical, passive computational chips. In contrast to electornic semiconductor computing, where the transistor is the "atom" of the logic gates, in photonics field there are numerous interesting nano-structures to be explored that are able to conduct binary or higher-order calculations.

The aim of this work is to research the co-existence of the Mach-Zehnder interferometer and a partial optical ring resonator. The expectations are to achieve all-optical switching nanophotonic device, in which a control beam releases and blocks the flow of the main one.

2. Theory

A crucial component of the design is the Mach-Zenhder interferometer itself. It comprises a Y-branch splitter and a Y-branch combiner, connected via waveguides with different lenghts. The unmatched lenghts cause phase shift (the light on the longer waveguide lags behind the light traversing the shorter waveguide). Ultimately, the induced phase-shift causes intereference.

In general, an imbalanced Mach-Zenhder interferometer can be implemented as per the below diagram:

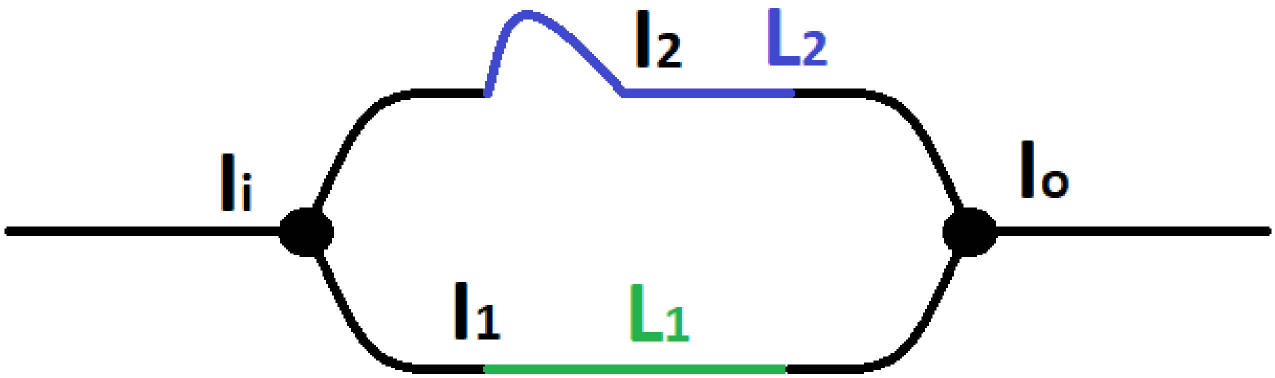

Fig. 1 – Imbalanced Mach-Zenhder interferometer concept

The output intensity level of the imbalanced Mach-Zenhder interferometer can be defined as follows:

$$Io=\frac{Ii}{2}[1+\cos(\beta\Delta L)]$$

Each arm between the splitter and the combiner has a propagation constant β.

$$\beta_1=\frac{(2\pi n_1)}{\lambda};\beta_2=\frac{(2\pi n_2)}{\lambda}$$

The waveguides have different lengths – L_1 and L_2. The length of L_2 can be represented as:

$$L_2=L_1+\Delta L$$

The output frequency response comb consists of a series peaks, following the transfer function of the interferometer. The distance between the peaks defines the free spectral range of the interferometer, namely “FSR”. The FSR depends on the ΔL.

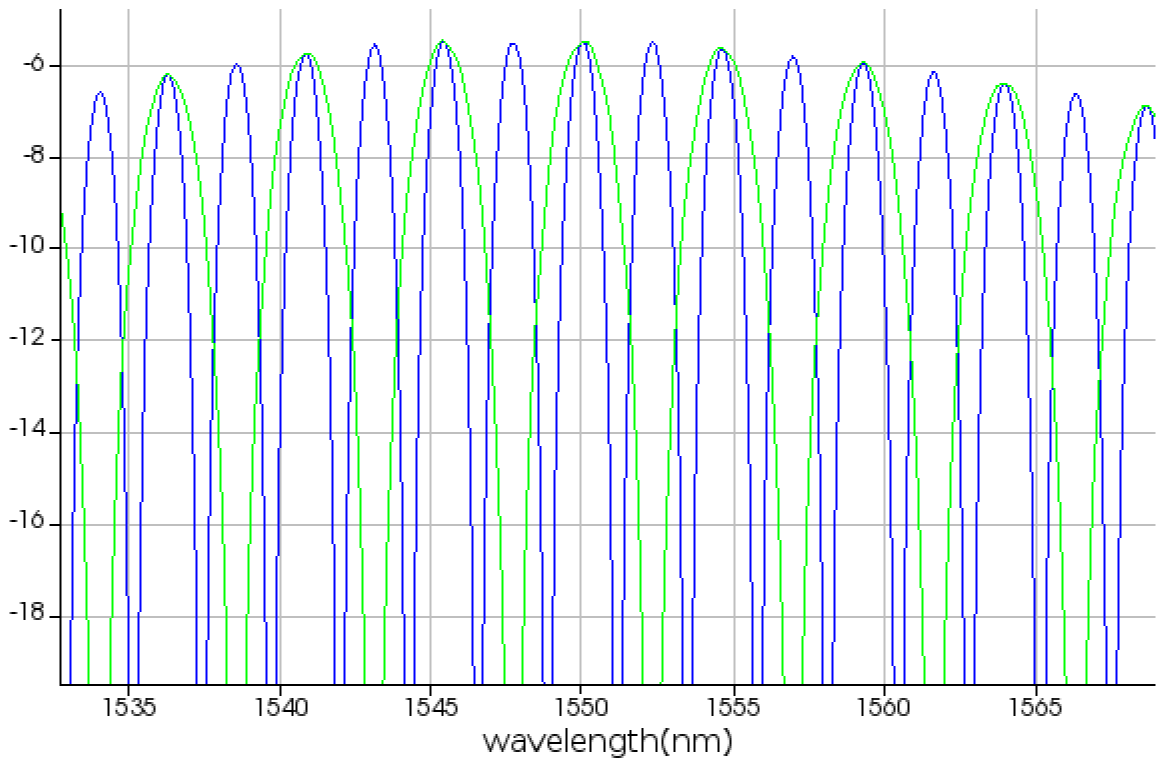

Fig. 2 – FSR of an imbalanced MZI with two different ΔL values

2.1 Fabrication technique

The proposed design is based on silicon-on-insulator (SOI) structures, placed on top of the silicon substrate. The waveguide material is pure silicon, wrapped by glass cladding (Fig. 1). Since the photonic integrated circuit targets the manufacturing capabilies ot SiEPIC, the silicon waveguide height is 220nm. This value is also common for a lot of silicon foundries around the globe. The mode of the waveguide is targeted for 1550nm center wavelength, observations of the spectrum will be within the 1500nm - 1600nm range.

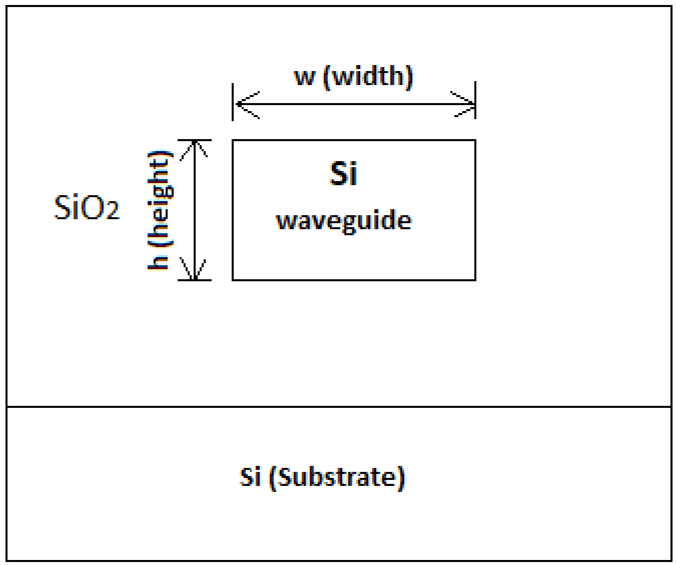

Fig. 3 – Sillicon wafer cross-section

2.2. Waveguide and mode

In order to cover the manufacturing capabilities and guarantee suitable optical confinement for the 1550nm wavelenght, the silicon waveguide has been modeled with Lumerical MODE – an Eigenmode solver software with simulation functionality.

Setting the width (w) to 500nm and the height (h) to 220nm, the simulation results report the following E-component intesity (Fig. 4) and indexes (Table 1) for Eigenmode #1 (this is the result for the horizontal polarisation):

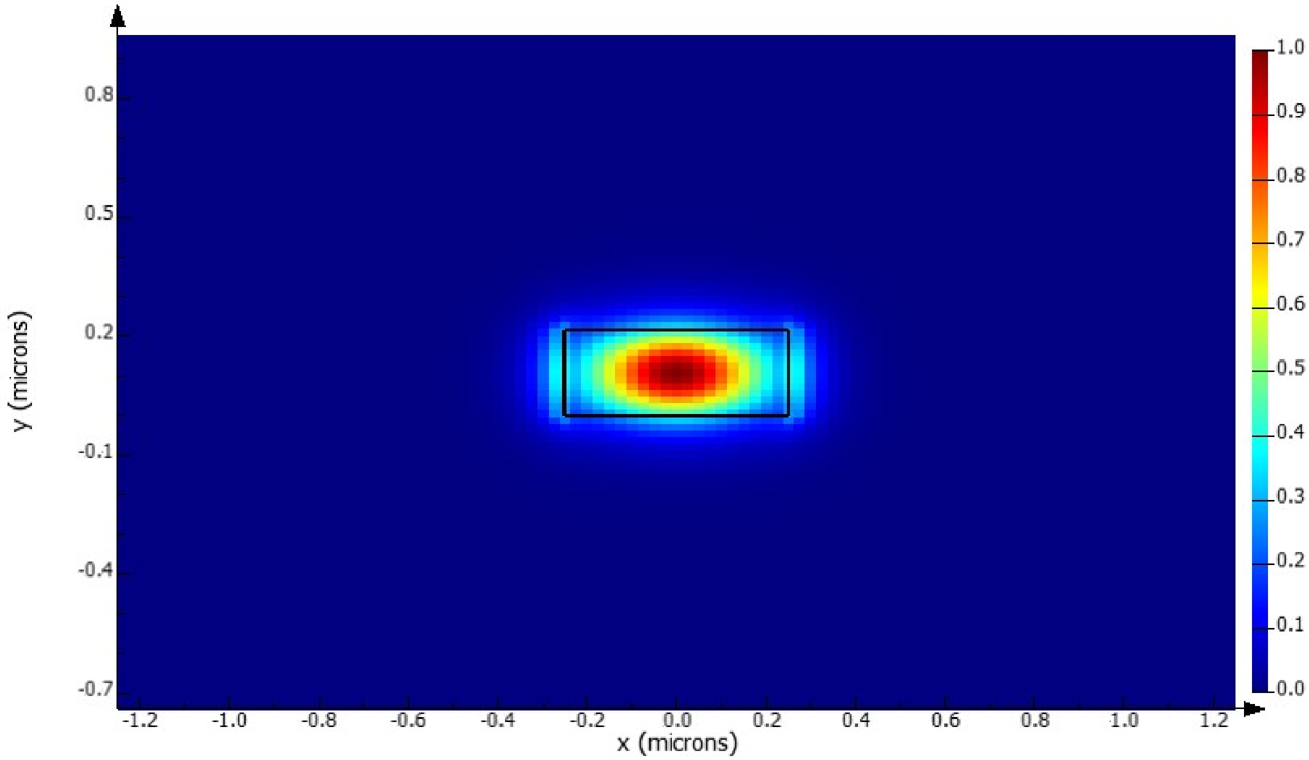

Fig. 4 – Mode #1 at 1550nm wavelength

Effective Index	2.443
Group Index	4.058
Loss (dB/cm)	1.4350e-05
TE polarization fraction (Ex)	98

Table 1 – Mode #1 parameters

The second mode (Eigenmode #2), corresponing to the vertical polarisation, has the following E-component (Fig. 5) intesity and indexes (Table 2):

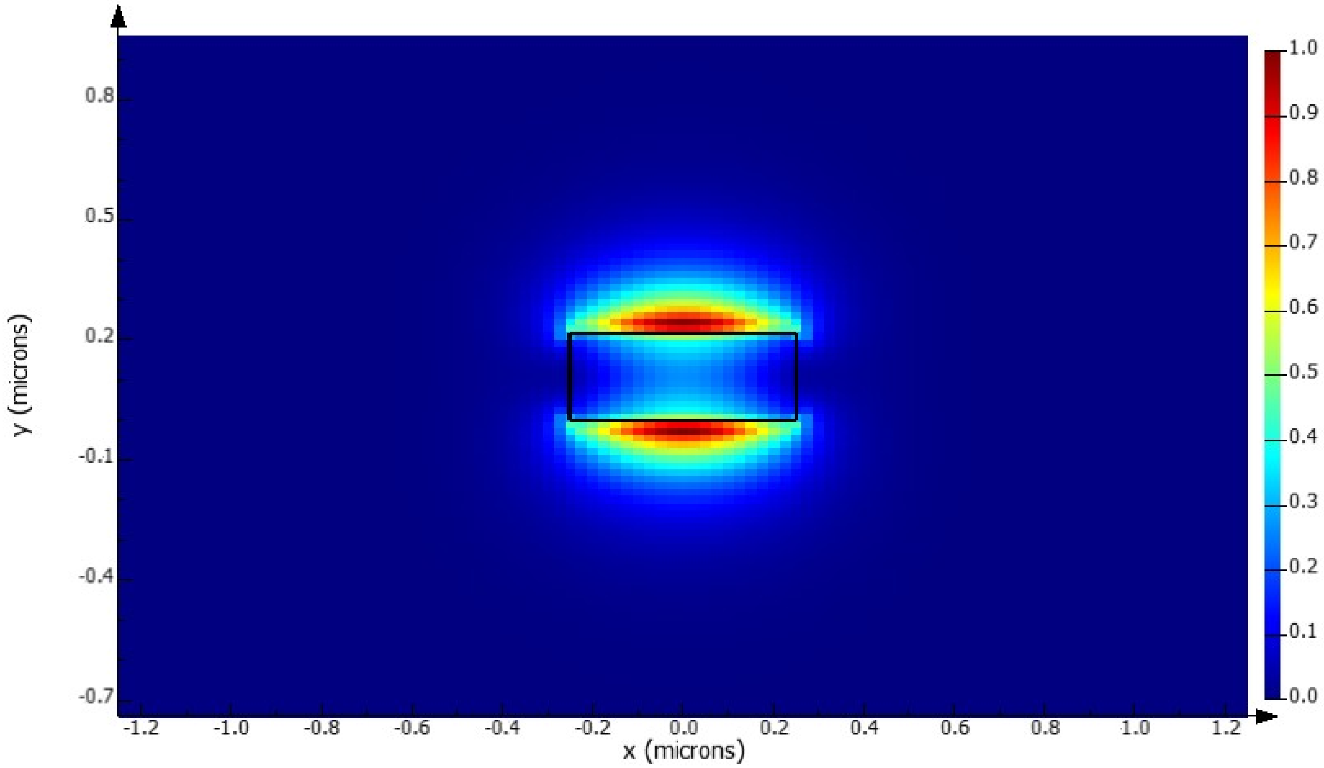

Fig. 5 – Mode #2 at 1550nm wavelength

Effective Index	1.767
Group Index	3.630
Loss (dB/cm)	6.5439e-05
TE polarization fraction (Ex)	4

Table 2 – Mode #2 parameters

For the sake of brevity, the second mode, corresponding to the vertical polarisation, will not be utilised. The device is designed by using components for horizotantally (quasi) polarised light instead.

From the Lumerica MODE simulation, the effective index can be extracted after a frequency sweep. The next figure represents the result:

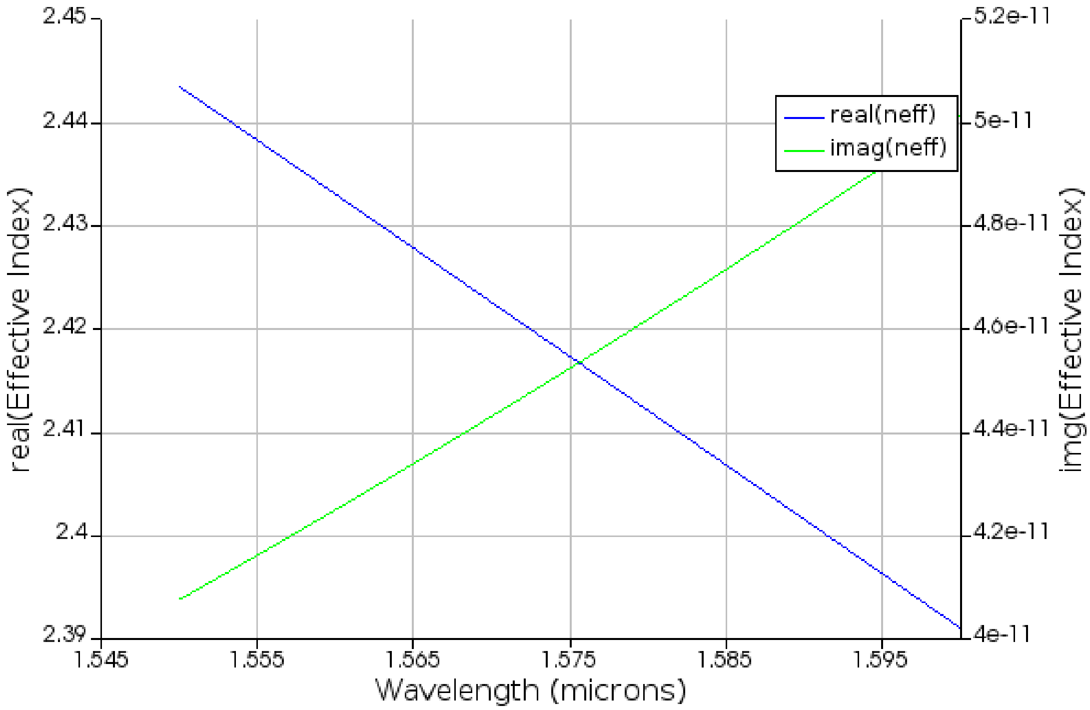

Fig. 6 – Si waveguide, effective index

The next step in the waveguide analysis is extraction of the group index:

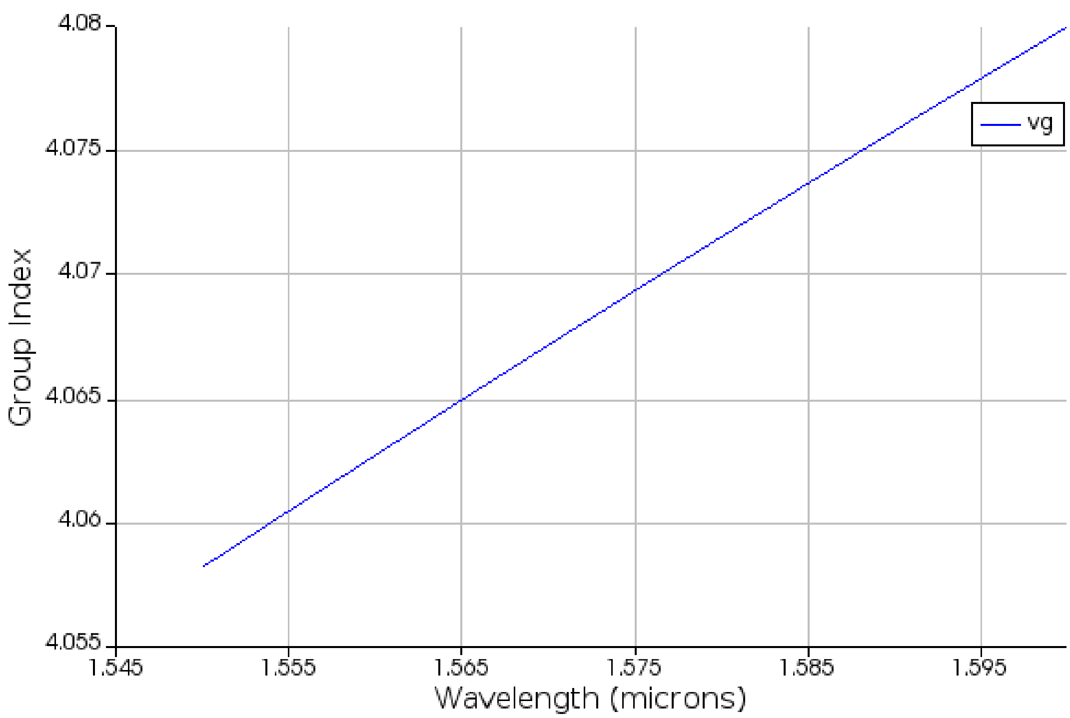

Fig. 7 – Si waveguide, group index

The effective index could also be described via a Taylor series expression (for the 1550nm wavelength):

$$neff(\lambda[\mu m]) = neff_1 + neff_2(\lambda - 1.55) + neff_3(\lambda - 1.55)^2$$

2.3. Y-Branch

The Y-Branch is a photonic structure that can be utilised either as a beam combiner or as a beam splitter.

The light intensity is defined as:

$$I_1 = I_2 = \frac{I_{input}}{2}$$

The electric field is defined as:

$$E_1 = E_2 = \frac{E_{input}}{\sqrt{2}}$$

The Y-Branch has a level (dB) to wavelength response function, also known as a transfer function. It will be extraceted from the S-paramaters compact model simulation in the next section (modeling).

2.4. Grating coupler

Coupling is the technique of inserting light from a waveguide with significantly large cross-section (or diameter) into a waveguide with smaller cross-section (or diameter). In the silicon photonics domain, the Grating coupler is the device that is used as optica I/O port.

Similarly to the Y-Branch, the grating coupler has a transfer function. It also will be extraceted from the S-paramaters compact model simulation in the next section (modeling).

3. Modeling

In order to model the Mach-Zehnder Interferometer, Lumerical INTERCONNECT will be used. The waveguide compact model is generated from Lumerical MODE and imported inside Lumerical INTERCONNECT. The Y-Branch and the Grating coupler are used as predefined S-parameter models (imported as files).

The Y-branch compact model is presented on the following graph:

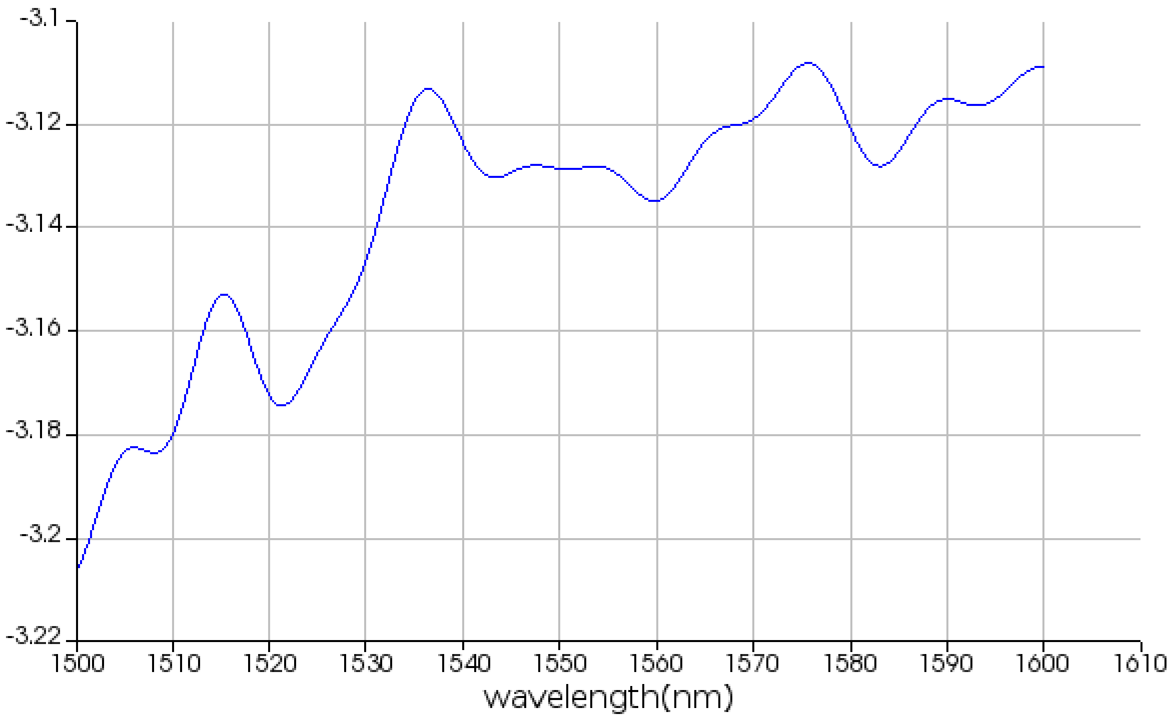

Fig. 8 – Y-branch transfer function, y-axis in dB

A graph for the Grating coupler compact model is provided as well:

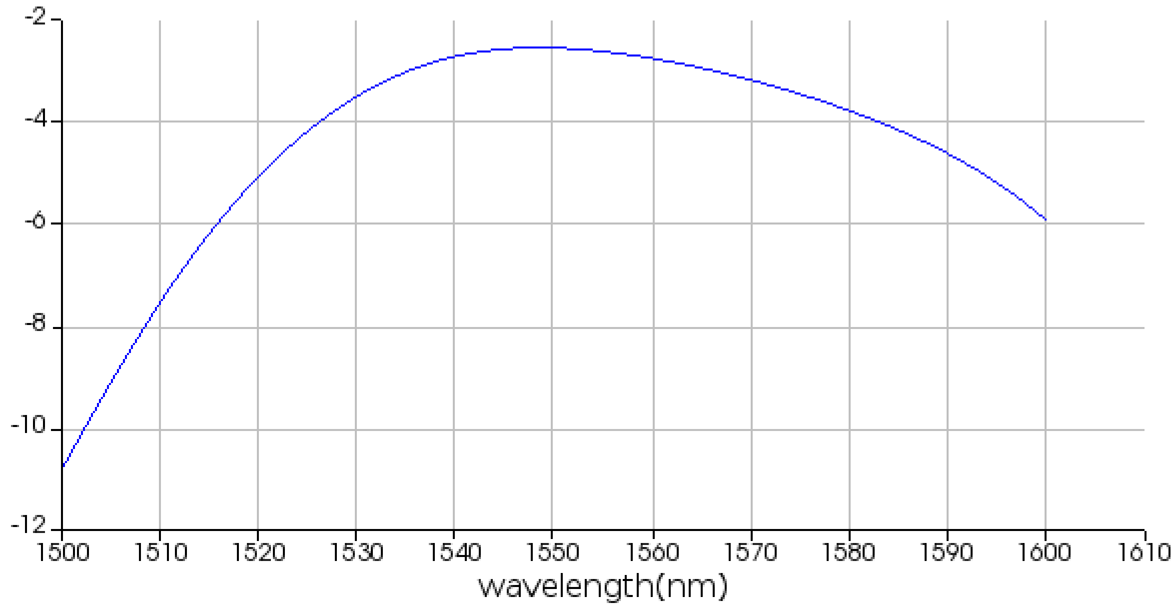

Fig. 9 – Grating coupler transfer function, y-axis in dB

In order to achieve the ΔL, two simulation variants will be modeled:
A. ΔL as simple waveguide mismatch (3.1). No elements from the SiEPIC PDK library will be used.
B. ΔL as a side of the half-ring resonator (3.2). The half-ring resonator is taken from the SiEPIC PDK library (EBeam).

3.1. Modeling ΔL as a waveguide mismatch

The following diagram represents the MZI model. The imbalance is caused by length mismatch between the waveguides connecting the arms of the Y-branches. It the below case, L_1 = 100um and L_2=450um.

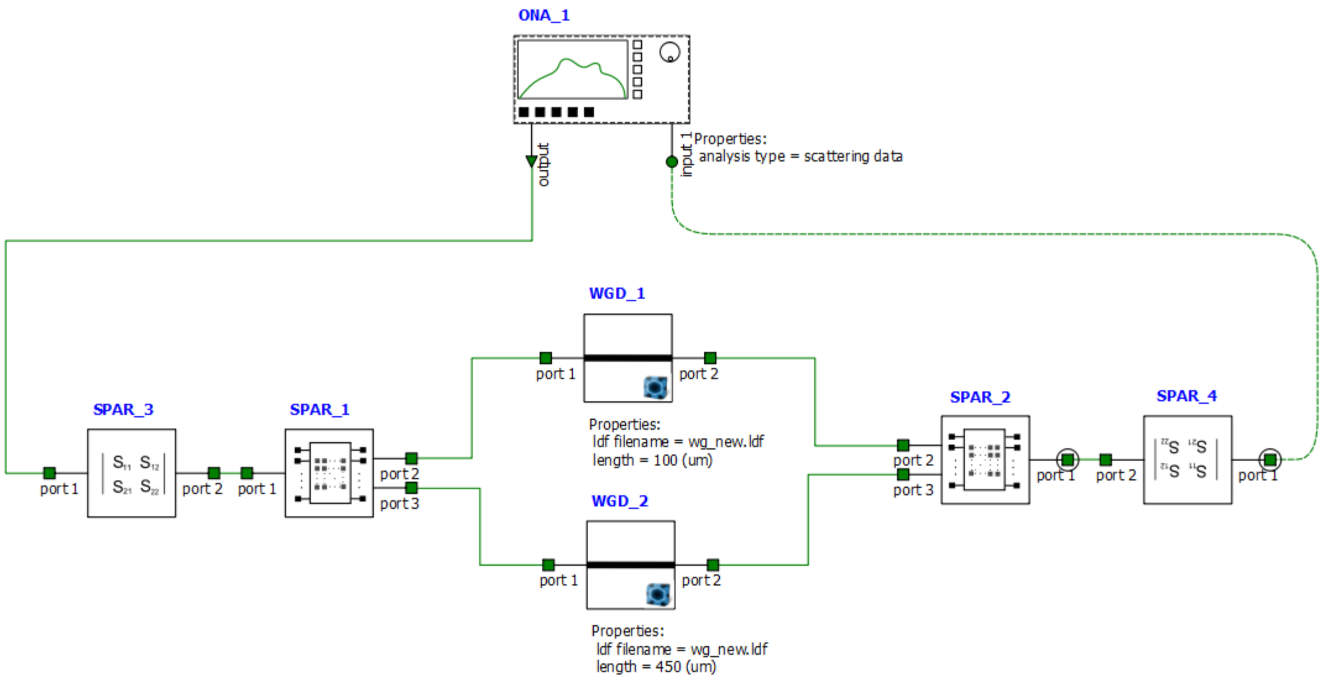

Fig. 10 – MZI diagram in Lumerical INTERCONNECT

The free spectrum range of the depicted photonic circuit after running the simulation has the following characteristics:

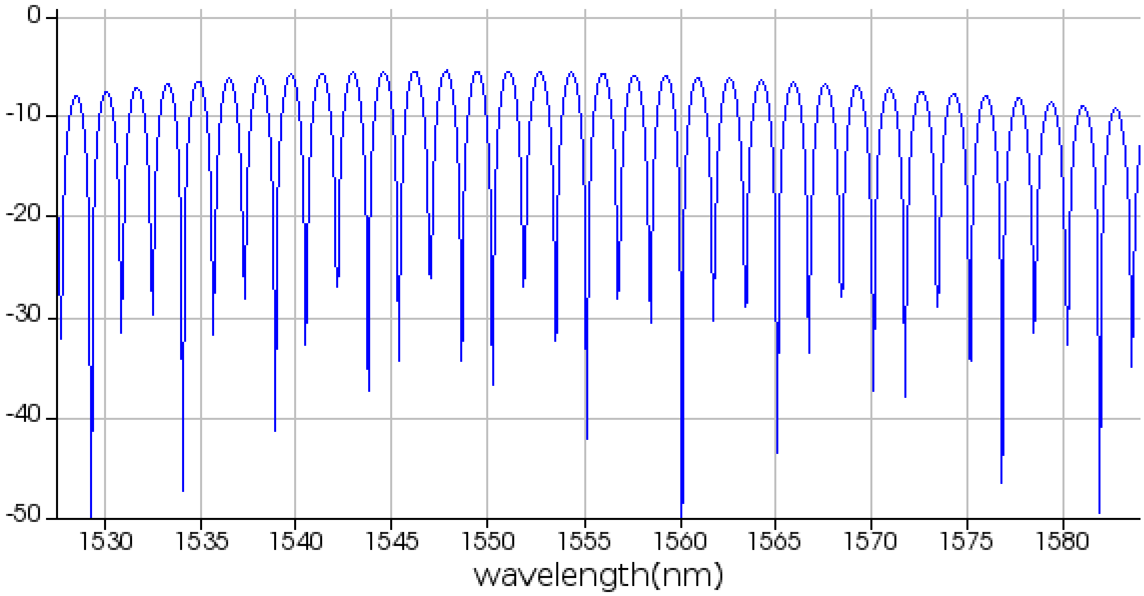

Fig. 11 – FSR (53nm), y-axis in dB

3.2. Modeling ΔL as a side of the half-ring resonator

For the experiment, a half-ring resonator object is taken from the EBeam PDK. Its dimensional characteristics are matched to the waveguide. The height is set to 220nm and the width is set to 500nm. The ring radius is 18um (the default value).

The experimental setup is the following:

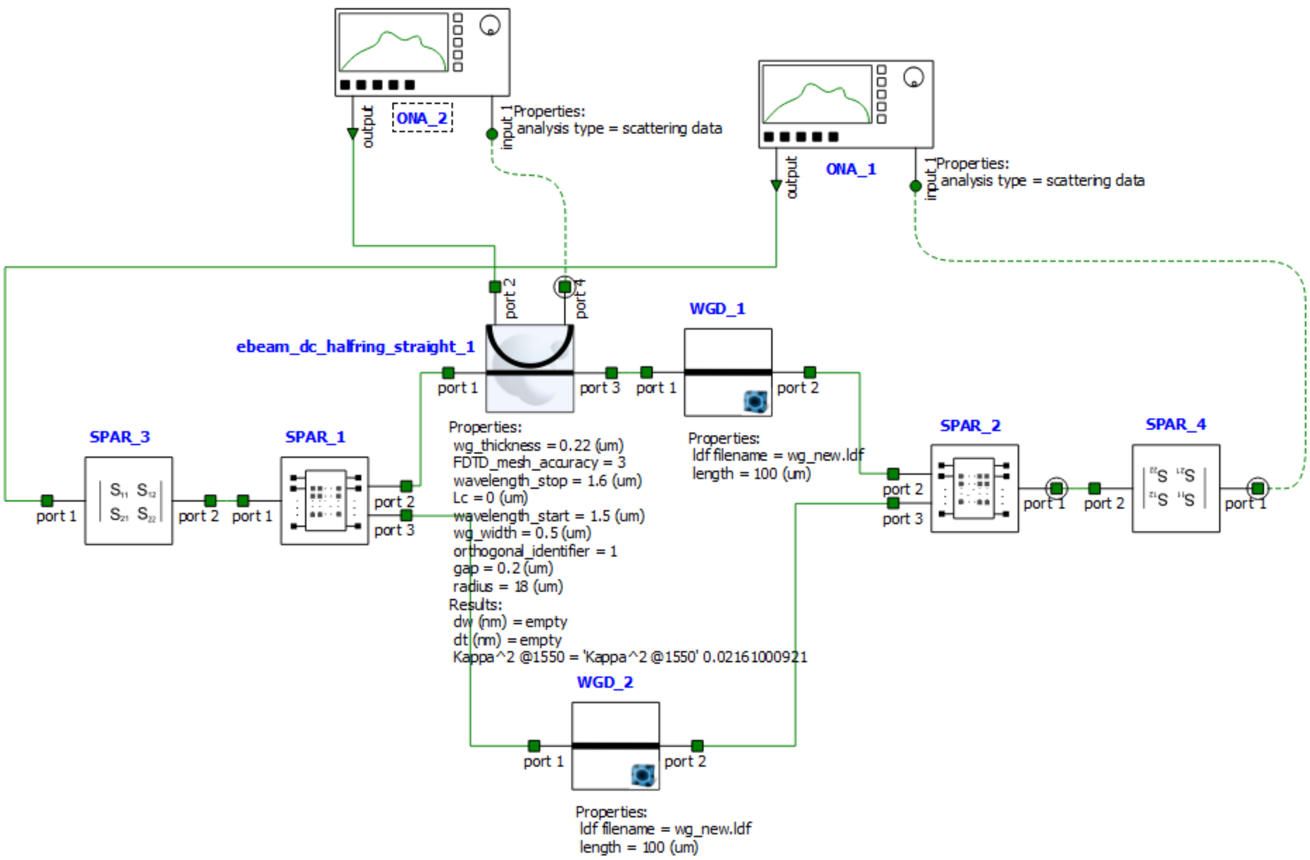

Fig. 12 – MZI with half-ring diagram in Lumerical INTERCONNECT

The half-ring resonator is connected in series with the MODE waveguide. Both L_1 and L_2 are 100um long. The straight waveguide component of the half-ring resonator causes some ΔL imbalance to the photonic circuit, so that FSR without a beam in the ring still resembles the one from a operational MZI.

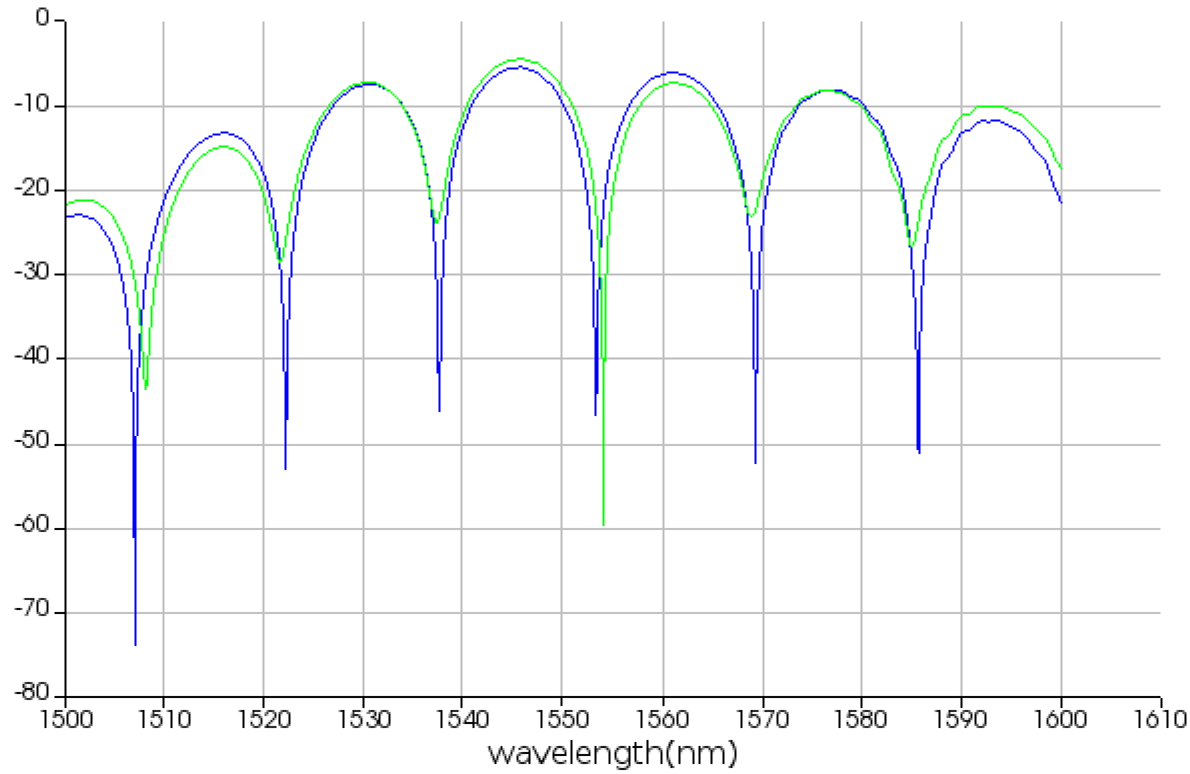

Fig. 13 – MZI with half-ring (blue – no light inside the ring | green – light inside the ring)

The optical network analyzers ONA_1 and ONA_2 are duplicate. ONA_2 serves only as a light source for injecting a beam inside the ring. Upon inserting a light beam in the ring, the FSR response changes slightly, serving an interesing topic for further exploration and experimentation.

Important note: The equivalent schematic in KLayout may be different from the above simulation. Since both MZI outputs will be routed to the optical outputs, the half-ring will be connected to the EBeam TE 1550nm terminator.

4. Layout

The photonic integrated circuit is designed in the free and open source tool KLayout, by using the SiEPIC library. The physical dimension are limited to a rectangular floor plan which is 605um in width and 410um in height. Four Grating couplers are used, arranged into an array with a step of 127um.

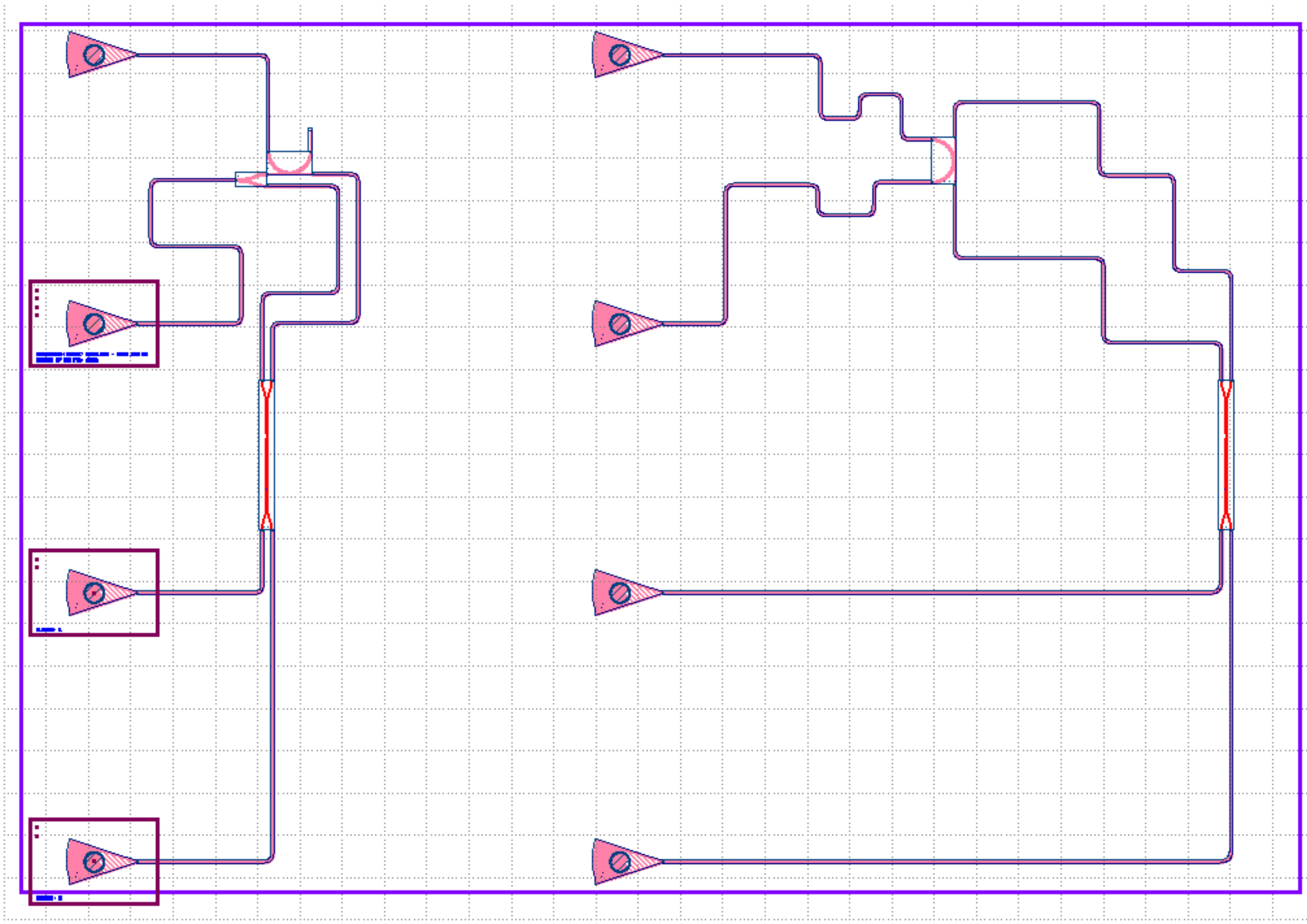

Fig. 14 – MZIs Layout

The half-ring resonator is routed to the upper-most Grating couper and terminated at the other end. The next figure represents the physical layout:

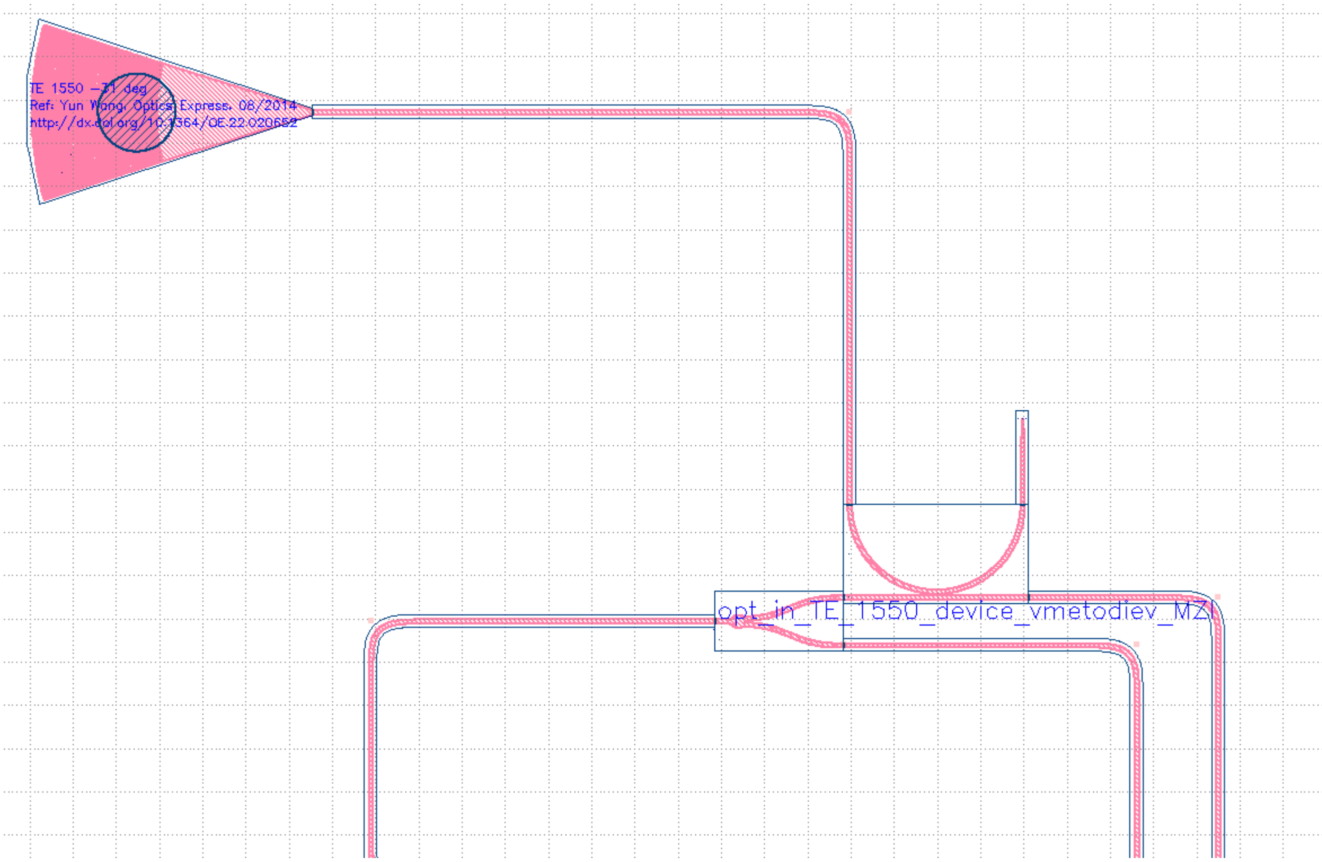

Fig. 15 – Half-ring resonator layout

5. Layout simulation

Two simulation cases have been covered – with and without laser input inside the half-ring resonator. KLayout to Lumerical INTERCONNECT integration depecits the spectra simulation results in both of the cases.

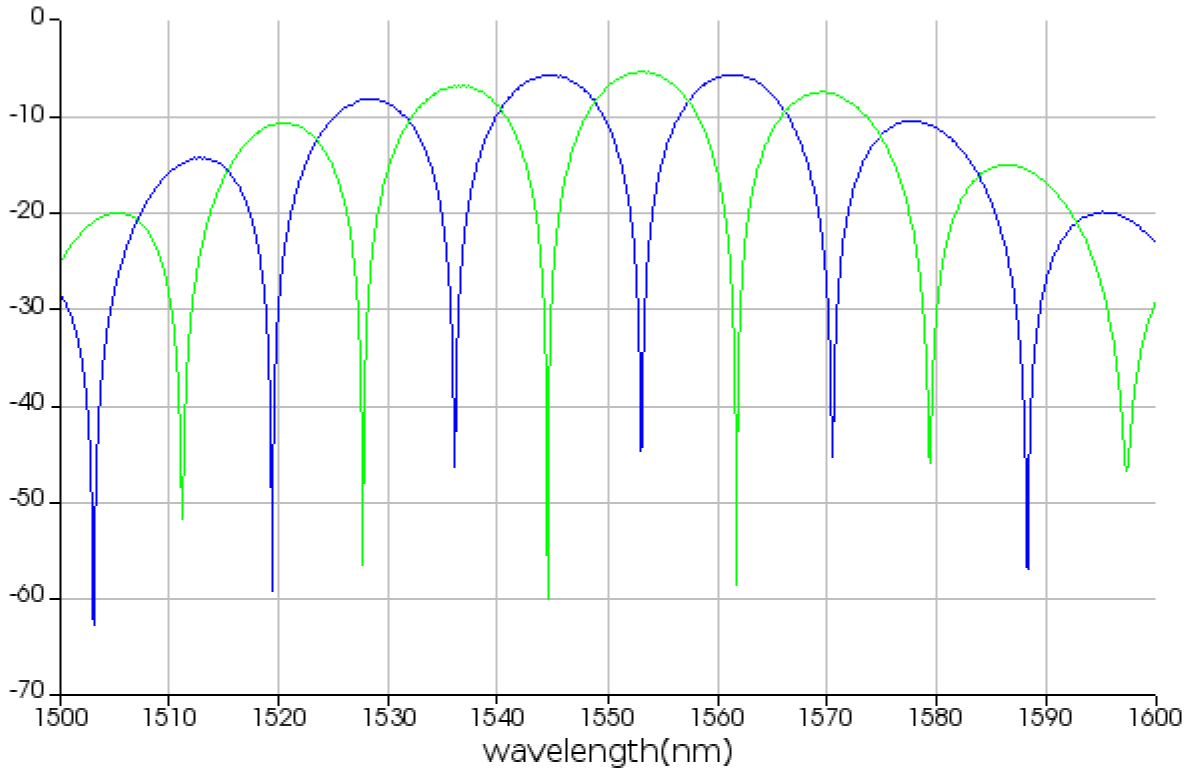

Fig. 16 – Spectrum, without laser inside the half-ring resonator layout, y-axis in dB
Green – Port 1 Grating coupler | Blue – Port 2 Grating coupler

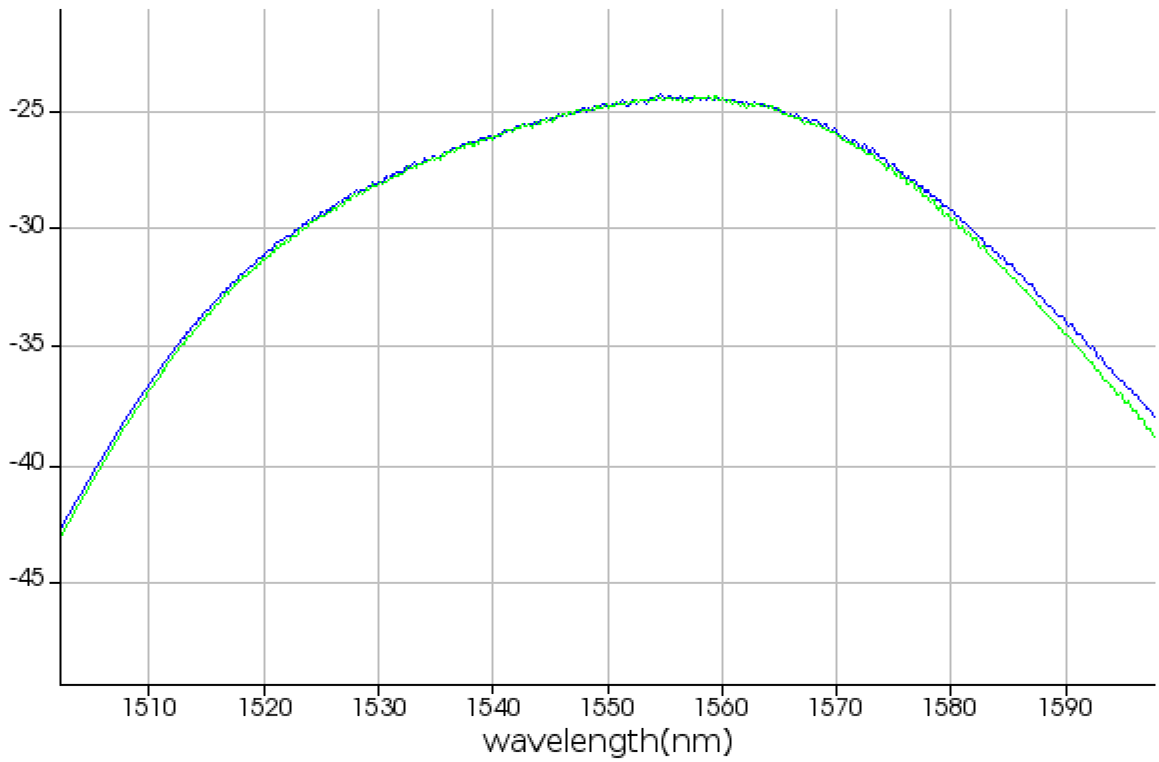

Fig. 17 – Spectrum, with laser inside the half-ring resonator layout, y-axis in dB
Green – Port 1 Grating coupler | Blue – Port 2 Grating coupler

6. Simulating the manufacturing variations

The Monte Carlo simulation method has been used to determine the possible deviations caused by the wafer production and the IC manufacturing. The KLayout module has been configured with the following parameters:

Wafer Variation
  Std. Dev (nm): 30
  Correlation Length (m): 4500e-6

Height Variation
  Std. Dev (nm): 4.7
  Correlation Length (m): 14e-6

Wafer to Wafer Variation
  Std. Dev (nm): 5.0

Thickness Variation:
  Std. Dev (nm): 2.0

The following graphs represent the peak gain and wavelengh as histograms.

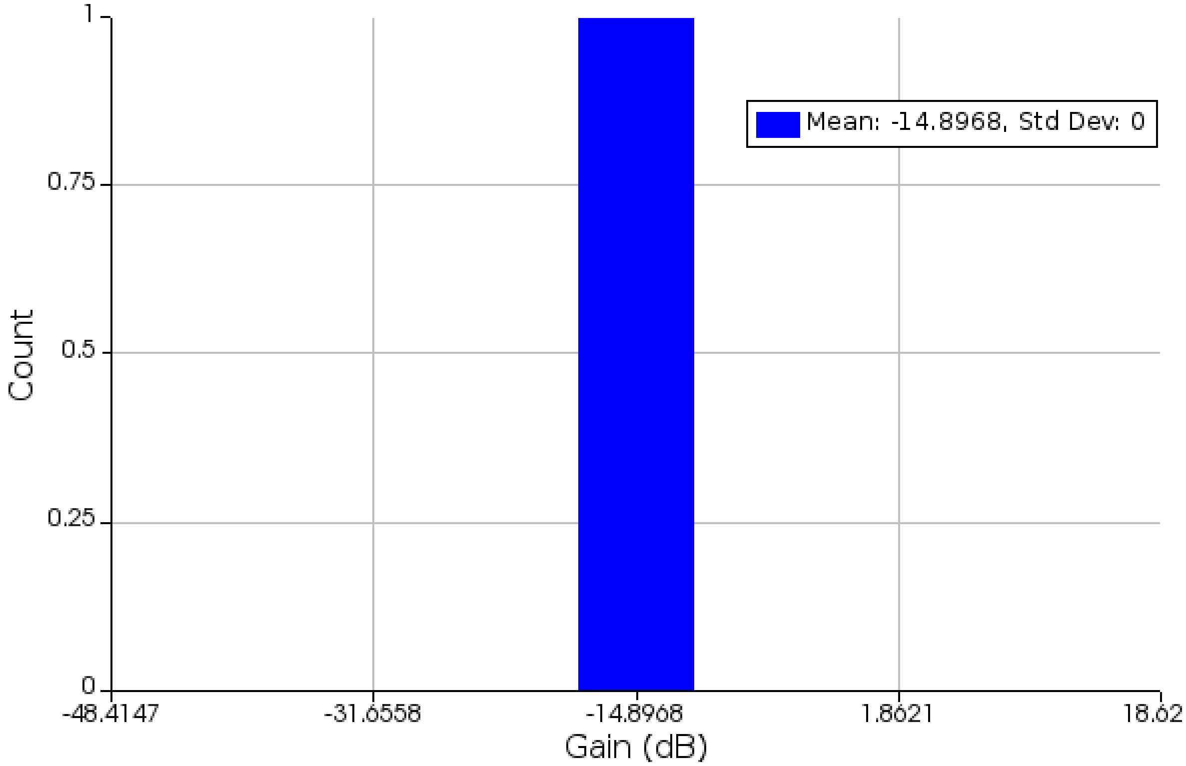

Fig. 18 – Peak gain after Monte Carlo simulation

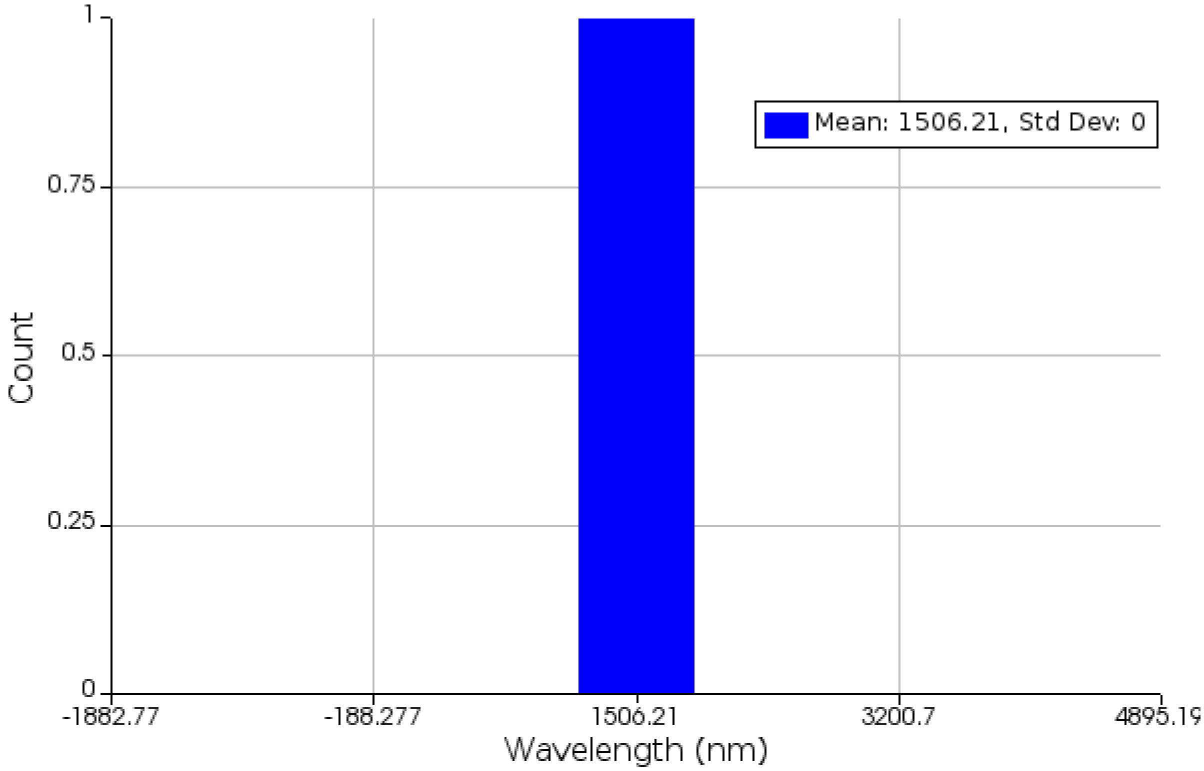

Fig. 19 – Wavelength after Monte Carlo simulation

Note: The simulation results, initiated from KLayout 0.27.5 (on Windows), do not seem adequate. It could be due to some software issue – either a bug or misconfiguration. Further analysis are needed. For now, all results and the related histograms should be ignored.

7. Manufacturing results

Unfortunately, the automated measurement equipment provides only a single laser source. Therefore, only the FSR defining a binary "1" will be observed at the output. By applying two phase aligned beams on both inputs, I expected to get the lower intensity levels, corresponding to binary state "0" (due to the induced destructive interference).

The FSR of MZI 1 looks like this:

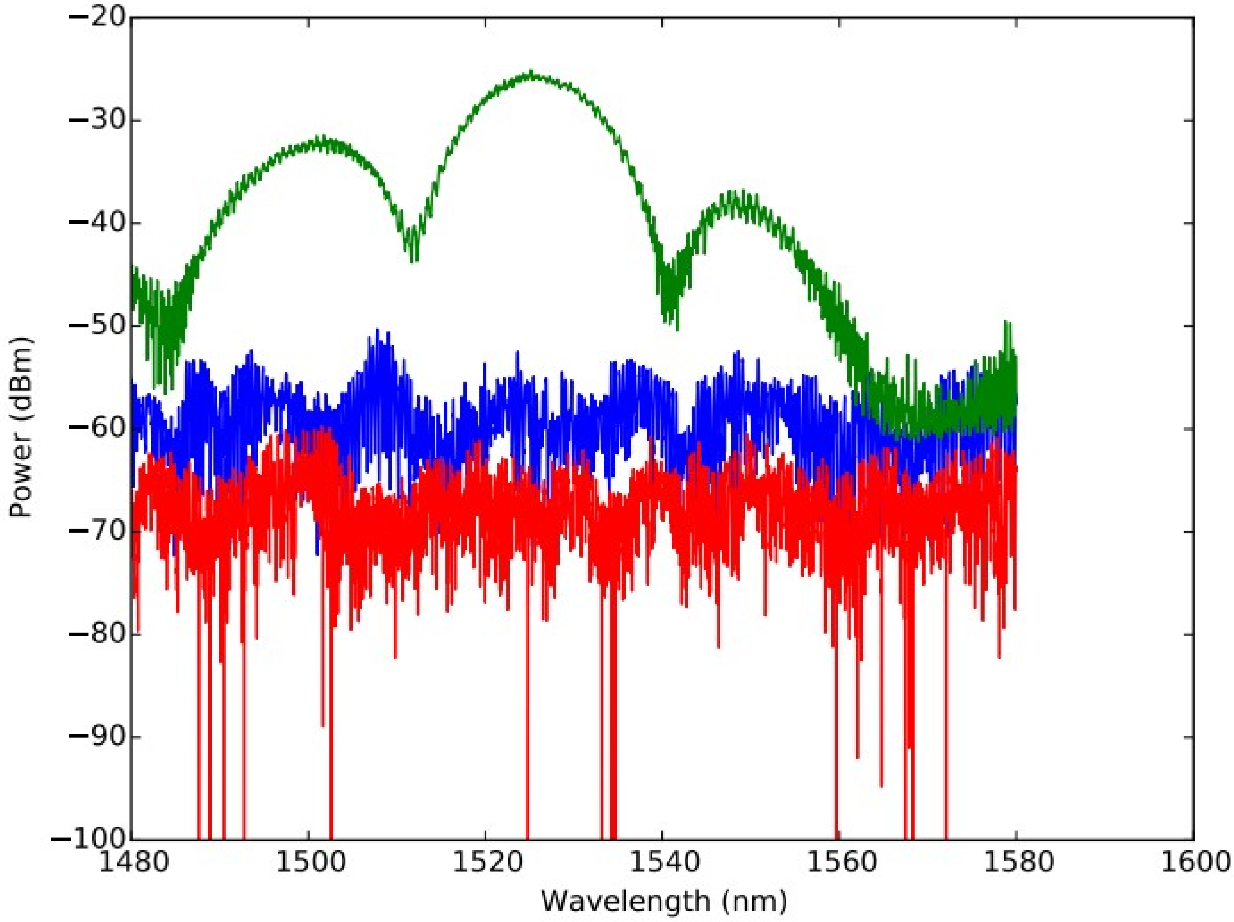

Fig. 20 – FSR of the manufactured MZI1

It could also be concluded that the intensity peaks do not correspond to the Lumerical simulation. The peak has shifted from 1550nm towards 1525nm. Due to the observed spectrum mismatch at that scale, there was no point in conducting further MATLAB filtering on the measurement data.

The FSR of MZI 2 should resemble the double-input simulation experiment. However, it is not realistic at all. It has been designed only for curiosity reasons. The FSR looks like this:

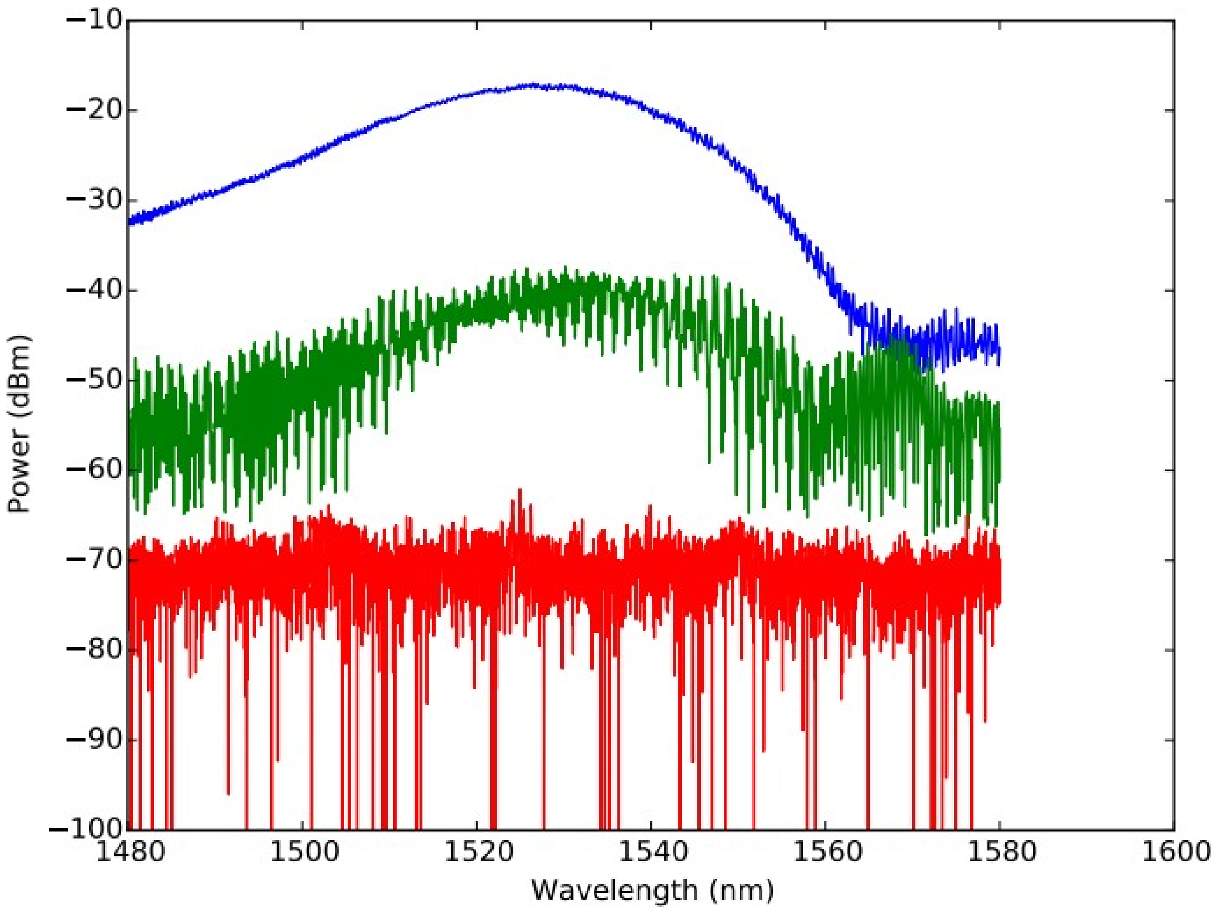

Fig. 21 – FSR of the manufactured MZI2

8. Conclusion

Based on the layout simulation results for the free spectral range (FSR), it could be assumed that ~15dB difference in the light intensity level at the outputs is enough to distinguish between the two independent logic states (0 and 1), thus proving the passive optical switching capability of the constructed photonic device.

Further research could be conducted in the future, using two simultatneous laser sources.